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Reinforced brick vault. The development of a construction system

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The aim of this paper is to study the way in which Eduardo Torroja used the reinforced brick vault, and to show that it is a system widely used for decades in Spain when Torroja begun to employ it. The principal characteristic of this construction system is the use of the brick wall as formwork to build up a reinforced concrete shell, where the masonry resists the compression stress as well. The main advantage of the system is it reduces cost by eliminating the need for formworks and scaffold.

FOREWORD

Stone materials have been used traditionally as construction materials.

The tensile resistance of these materials are negligible: to improve the performance of stone materials relating to tensile resistance several solutions have been proposed. The aim of these solutions is to increase the tensile resistance. The increase of iron production in the 18^{th} century increase the use of metallic parts in masonry.[1]

Use of iron elements to reinforce masonry structures

From 1825 to 1843 the engineer Marc Isambard Brunel designed the tunnel under the Thames where among other innovative ideas, he put into practice the use of masonry walls reinforced with steel to form the tunnel walls. (Hansen 1933).

The success obtained with this use of metallic reinforcement inside the masonry leads him to design a new system mixing steel with masonry. During the following years he built masonry arcs reinforced with metallic elements, and a series of 21ft span T-beams made in brick reinforced with 1.25 inch*0.65 inch steel strips. This kind of arcs had been tested for two years and finally in 1838 they broke under a load of 6832 lb.

Hansen (1933) shows several tests carried out in 1925 in EEUU where several ways to organize beams (the beams were constructed in brick reinforced with steel bars or strips, using or not transversal reinforcement) had being studied. The main conclusion was that the hypothesis used in concrete structures calculations could also be used to calculate brick reinforced units. The ratio between modulus of elasticity of steel to masonry is n=20.

Construction of mortar reinforced with iron mesh thin shells

One of the main application of reinforced concrete describe in the first patents was the vault construction.

One of these is the Cottencin patent. This patent proposes a system to build up thin shells in "plastic material" reinforced with a metallic mesh big enough

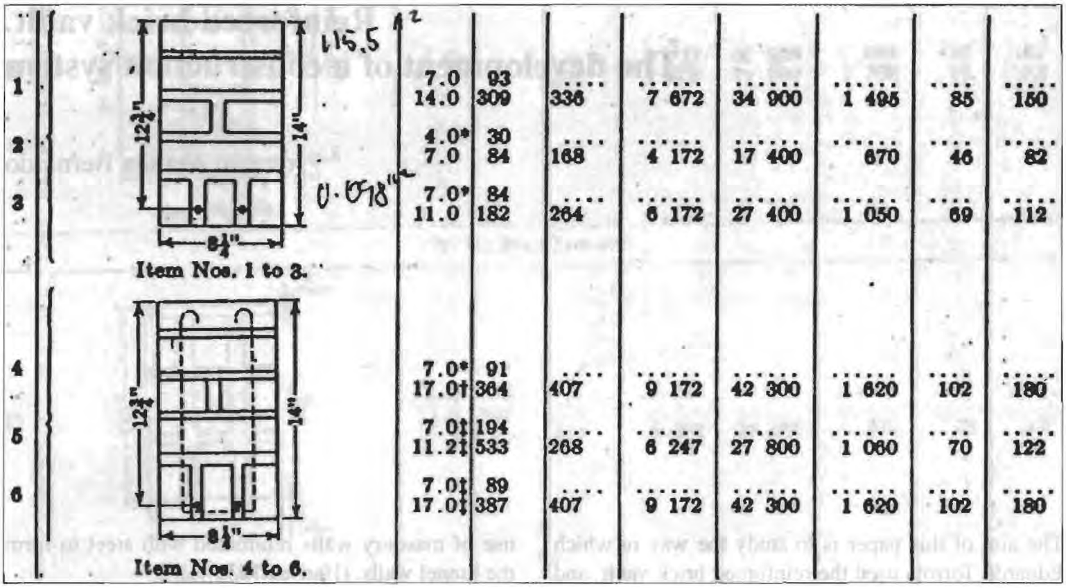

Figure 1

Transversal section of a beam built with bricks and reinforced with steel bars in the lower face of the beam. The dotted line represents the transversal reinforcement that is not used in every beam tested.

to resist the stress applied. The innovation was the way to produce the metallic framework. In the description of the possibilities for the new products, it states that it is fit for masonry[2].

Timbrel vault

The construction of timbrel vault was a common structural system used in Spain. The system was based on the use of thin hollow bricks (about 4 cm deep) called "rasillas". With these special bricks several layers (generally two or three) were build. The first one is jointed with quick setting plaster mortar. With this system, the centring is not necessary, and only light arch brace are needed, which make easier the redesign. Next layer is jointed with cement mortar.[3]

Timbrel vault reinforced with iron wires

From the eighteen eighties Antonio Macia built in Spain concrete works using the Monier's Patent. In 1889 Macia patented a new system consisting in reinforcing one or more brick layer masonry with a mesh embedded in cement mortar. With this material he designed sewers, pipes, depot and cupules.

That system consists in built one or more layers of hollow thin tiles and reinforced them with a mesh of iron wires that is covered with mortar of Portland cement.

In the patent text, it is mentioned that no structural calculation is included due to the fact that it is acceptable to consider the resistance of the new element as the addition of metallic elements, mortar and bricks ones, and the traditional general mechanics theory applied to constructions could be used.

Conclusions

The use of different types of masonry reinforced with steel bars or strips were a system widely knew and used around the world in the first decades of the 20^{Th} century.

This kind of structures are analysed like reinforced concrete structures

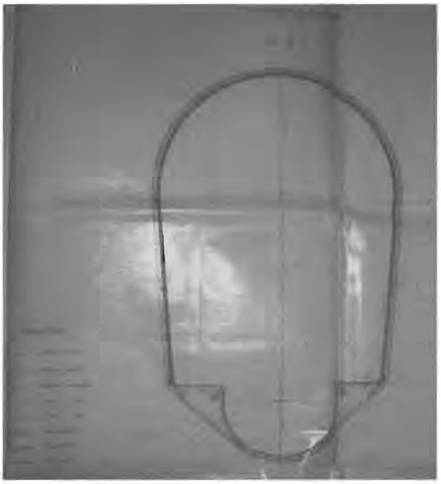

Figure 2
Section of a sewer constructed following the Macia's system. It consists in a "rasilla" layer cover in the inner part by a cement mortar rendering and with concrete reinforced with steel bars in the external face.

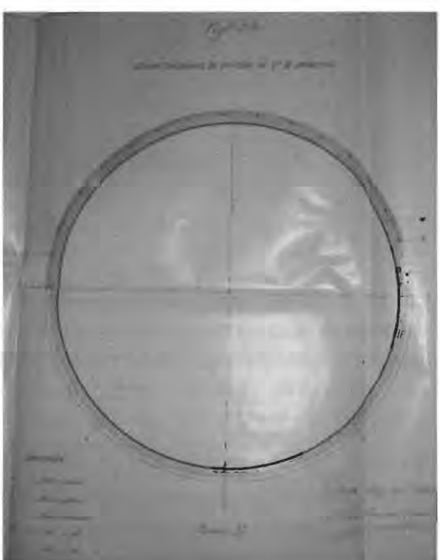

Figura 3
Transversal section of a 2 m diameter pipe built up following the Macia's system. It consists in two "rasillas" layers cover in the inner part by a cement mortar rendering and with concrete reinforced by flat ion strips in the circumferential direction and with round bars in the longitudinal direction Sección

Reinforced Timbrel vault First Torroja's woks. Foundations caissons of Sancti Petri's Bridge, Cadiz[5]

Foundation caissons are auxiliary works used to excavate the foundation of bridge pillars in soils with some determined characteristics. In Cadiz Bay this system was commonly used in the nineteen twenties, and was well known by Torroja.
In those days, foundation caissons were construction reinforced concrete with a shape similar to an up side down mortar box. Doing this, it was possible to create a chamber where the workers could stay and excavate down to the rock. At the same time the caissons were buried are enlarged to maintain the upper part over the water level.

In 1926 Torroja presented a design for the foundation of Sancti Petris's bridge. In this design he propose a cylinder shape caisson. The caissons consisted of two concentric walls. The external one had a 7,00 m diameter. In the lower 6,00 m the diameter was enlarged to give 7,50 m in the bottom of the caisson. The inner cylinder was 1,00 m in diameter to allow the workers to pass through it.

This structure has two peculiarities: The shape, is a section of a revolution hyperboloid, and the construction system, is a vault made with a thin layer reinforced with a 4 cm thick reinforced concrete layer.

The shape of the caisson

The section of the inner cylinder in the part situated between the base and the vertical duct is a double curvature surface with different signs (transversal section is a hyperbole). These conditions mean that in a reinforced concrete section the reinforcement could be set-in following the direction of the straight lines of the resultant hyperboloid (figure 5).

Once the caisson is constructed, it is placed in the position, and submerged to where the excavation has to begin. Then, the space between the two cylinders is filled with concrete. When the excavation takes place, the structure is a vertical cylinder. The dimensions of the cylinder are 7,50 m diameter and 50 cm thick at the base, the diameter goes to 7,00 m and the thickness goes to 3 m at the 6,00 m from the bottom. After this elevation, it is a continuous 7,00 m diameter and 3 m thickness cylinder.

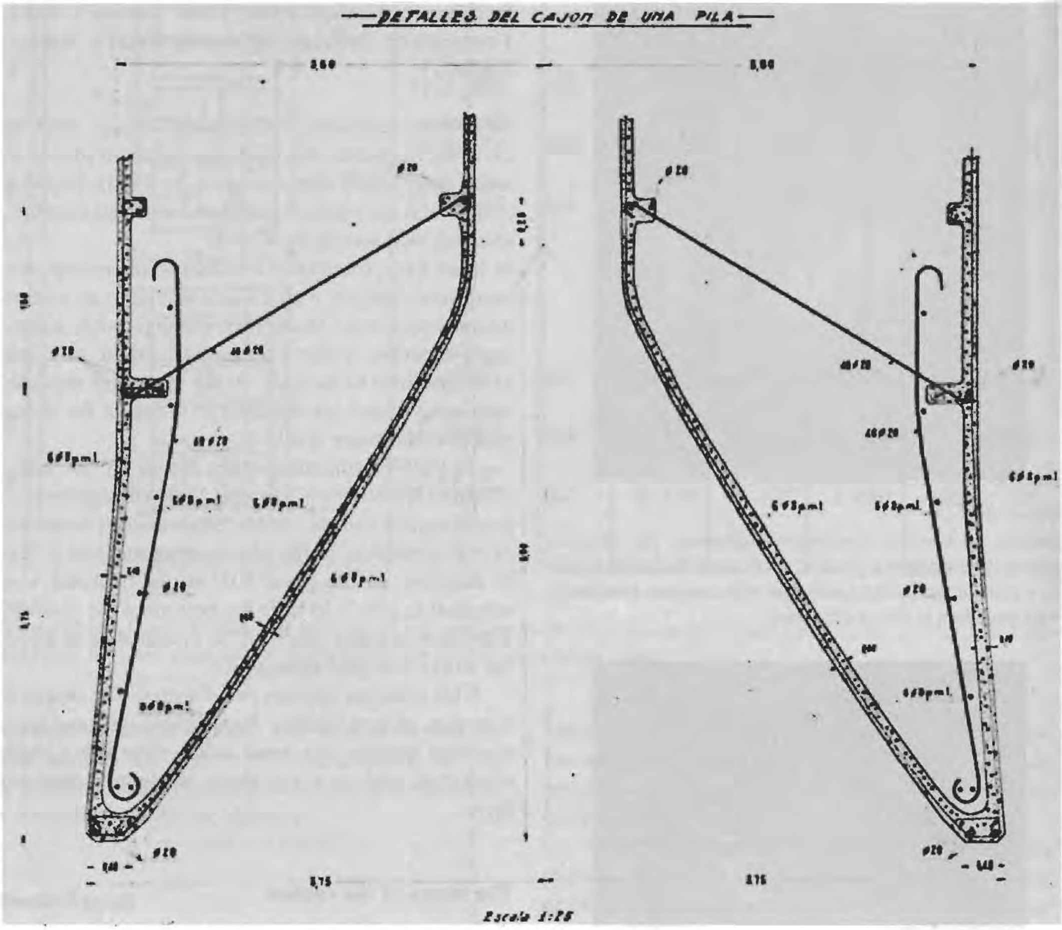

Figure 4
Design of the foundations caissons project of Santi Petri's bridge. They show the two walls of the cylinder which in the lower part has the shape of one hyperbola. In the project, the structure is in reinforced concrete. There are not references to the timbrel vault.

To analyse the structure it is assumed that it is a perfectly elastic mass. In the technical documents accompanying the design Torroja mentioned the Poschl procedure (Berlin 1922), but it is stated that " The solution to the equations system is extremely difficult,....we do not know any theoretical study for practical integration in the case of non uniform loads" so" we think it is useless to develop all the calculation here....." The inner wall with a hyperboloid shape is submitted to the uniform pressure of compressed air and the analysis is just to assume the elemental equilibrium in a section. It is assumed as well that only the steel resists the compression and tensile forces.

The construction of the caisson

The design specifies that the caisson is made in reinforced concrete (page 7 in the technical documents of the project), but it do not say anything about how to made this special shape. Nevertheless the graphics

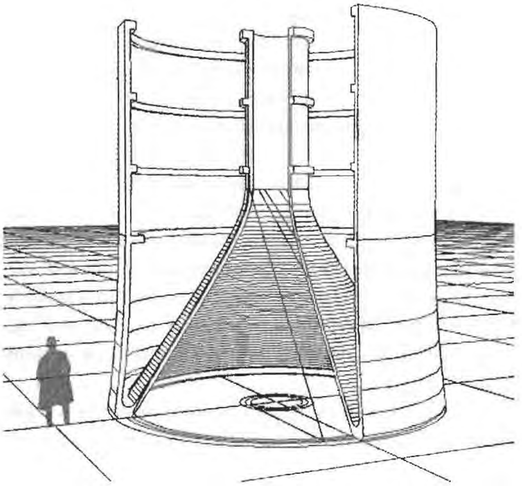

Figure 5
Foundation caisson scheme. One of the straight lines is marked to show the position in which the reinforcement could be set-in avoiding the need for curving the reinforcement bars.

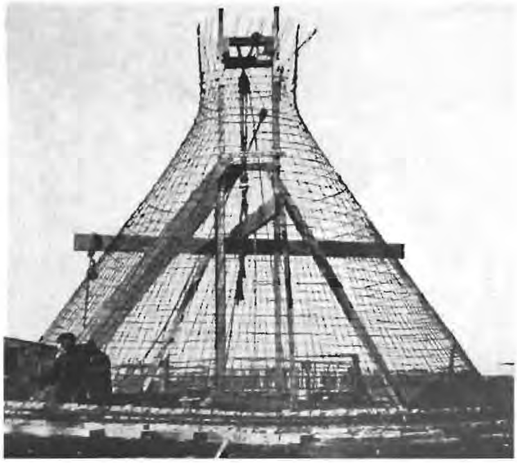

Figure 6
To found the pillars of the bridge some caissons were built. From the documents we have, it is deduced that two construction methods were used. The figure shows one of them consisting in place the inner profile shaped reinforcement and a closed to it a wall in the inner part to be used as a formwork for the following concrete filling. Down left it is possible to see a worker making the "rasillas" masonry.

are clear and it shows that at least two different procedures to build up the caissons where used:
Redesign the reinforcement using the shape of the caisson and build closed to it a wall made with "rasillas" to be used as formwork. (Figure 6).

b) To erect the shape of the caisson with a "rasillas' wall and put the reinforcement over the wall and later the concrete (figures 7 and 8).

In both cases the used of timbrel vaults is due to constructive needs. A well known constructive system and used in a different kind of works is used. But in this case is used as auxiliary work to obtain a reinforced concrete surface with a determined shape. Doing this the need of a formwork in wood is eliminated and the cost of the work is reduced.

The way to construct is very similar to this one patented by Maciá approximately 30 years before. It is possible to state that this way of construct concrete laminar structures was known and used widely in Spain at least 30 years before

Conclusions

In 1925 when Torroja begun to work the first paraboloid hyperbolic shape concrete reinforced shells, had been erected. It was a technique not extended but known.

In Spain in those days the use of masonry as auxiliary work to build up laminar structures with simple shapes, generally in a cylindrical section was a spread system and was the object of several patents.

The innovation introduced by Toroja is to used a known system and apply it to a regulated surface.

In the structural analysis the material is considered homogenous and elastic

The churches in the Pirineos. The possibilities of a construction system

Through the year 1953, after a travel to South America, where Torroja visited several countries giving courses and seminars, Torroja designed some works to "Empresa Nacional Hidroeléctrica Ribagorzana" (ENHER). The most important one was the vault dam in Canelles. In addition to this project, he made some churches designs to be constructed in the area near the Noguera Ribagorzana

Figure 7
It is possible to appreciate the conditions needed for the timbrel construction. Just some wooden simple guides used for the redesign and to survey the way in which the masonry is constructed. When the masonry is finished, the reinforcement and the concrete are placed. Down right it is possible to appreciate the wood board that acts as a guide

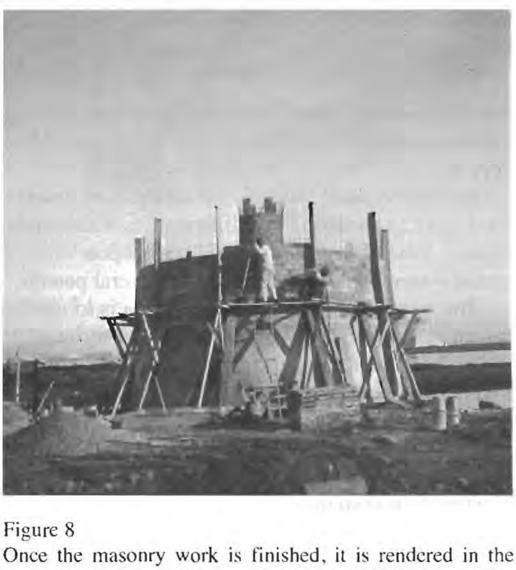

Figure 8
Once the masonry work is finished, it is rendered in the external part and in the inner part the reinforcement is placed between the two brick layers. It is possible to see the vertical guidance to survey the external face shape.

River: Xerrallo's church, Sancti Spirit's mountain hut and Pont de Suert's church.

In all of these projects, to make the roofing vaults with two or three rasilla layer reinforced with a reinforced concrete layer were used. The list of shapes is extensive, they use: sferical domes, pointed arches, pointed domes and pointed vaults and double curvature surfaces generates whith spirals curves, ...

In Oschendorf 2003, the coincidence with the Torroja's travel to south America and the construction of these roofing structures using a system mixing masonry and steel reinforcements was discussed. We do not know if Torroja meet the Eladio Dieste's Works in Uruguay, but it is possible to state that the system used by Torroja is fully different to the system used by Dieste.

In that moment he was working in his book "Razon y ser de los tipos estructurales" where Torroja regrets that architects were not be able to explore the reinforced vaults shape possibilities.

It is possible to understand the design of these churches as a research of the possibilities to build different shapes using timbrel vaults reinforced with a layer of reinforced concrete.

The shape of the nave's roofing

The design of the church is a nave with a rectangular plant with an apse in one end and a baptistery and a communal hall. In each part a different type of roofing is used, but all of them made using timbrel reinforced vaults. All the shapes are obtained from geometrical expressions. Arcs of circles, parabola, logarithmic spirals, ellipsis...

The only shape we will study is the central nave's roofing. It consist in five parts of 5,00 m wide each and 12,00 m span. The roofing of each part is an pointed arc who begin over two niches with ellipsoid shape. The particularity is the way to build up each part. It consist in a surface with double curvature, which transversal section is an circle arc with varable diameter. The diameter becomes bigger arriving to the keystone.

The transversal section of the modulus is a circumference arch with a variable thickness defined by two arcs with different diameter. The inner one is a projection of an warped curve which projection over a longitudinal plan is a parabola beginning perpendicularly to the lower niche and has a vertical tangent in the upper part (figure 13). These two conditions give the analytical expression for the parabola.

To determine the geometrical shape of the lobule, 26 points over the edge of the curve are defined using the coordinates in the longitudinal projection. Each of these points is used as beginning of an circumference arc situated in the plan defined by the point itself and the symmetrical one placed in the warped curve. All the planes containing this arches, rotate about the axis signed in the figure 14 like "eje de giro del plano de las generatrices."

It is difficult to express in an analytical way this surface, but with the data given in the documents accompany the design, it is possible to build simples arch braces with a well-defined section. These arch braces will be used as a guide to give an idea of where to put the first layer of "rasillas."

This project shows that it is possible to build really complex geometries using the timbrel vault combined with reinforced concrete. This method allows building shells with complex shapes eliminating the formwork costs.

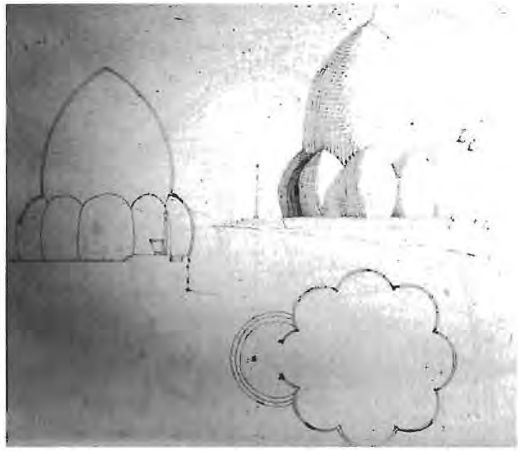

Figure 9
Drafts for the Xerallo's chrch project. The cover is made whit the same system used in the baptistery of the Pont de Suert's church.

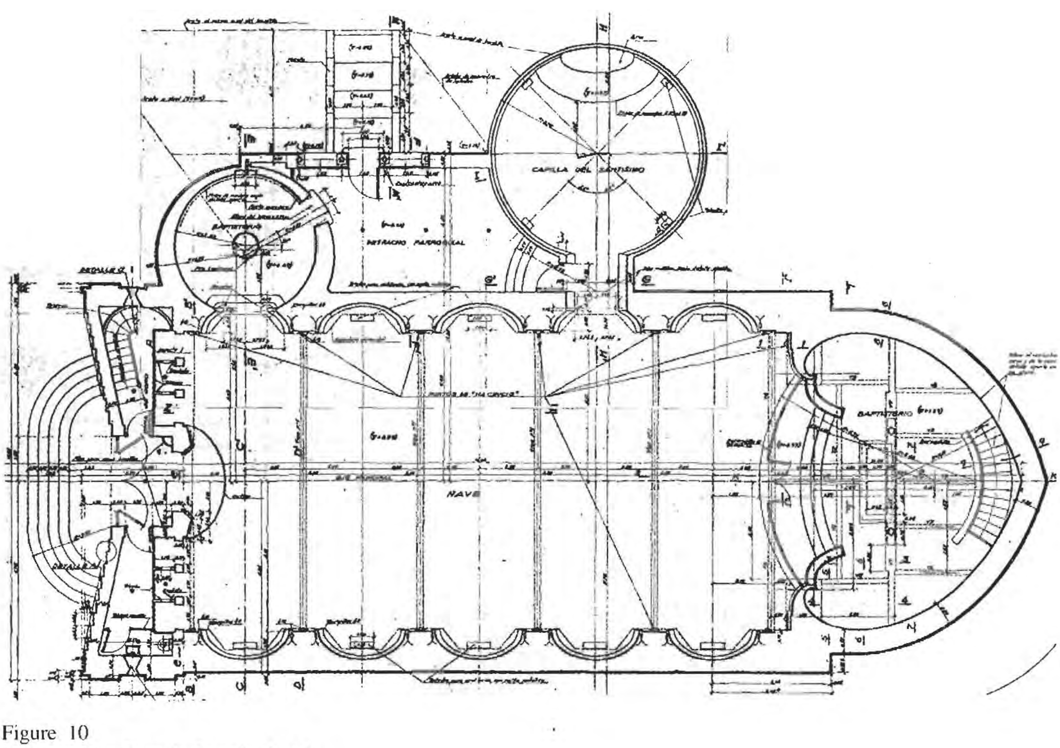

Figure 10
Design of the Pont de Suert's church.

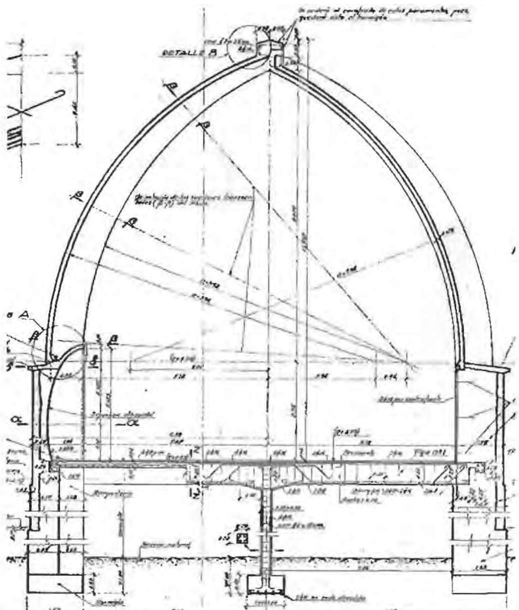

Figure 11
Transversal section of the Pont de Suert's church.

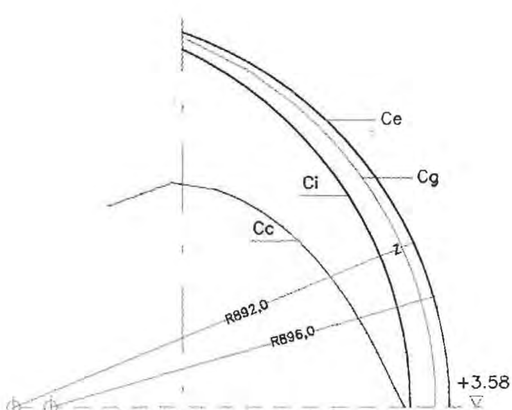

Figure 12
Geometrical schema of the transversal section

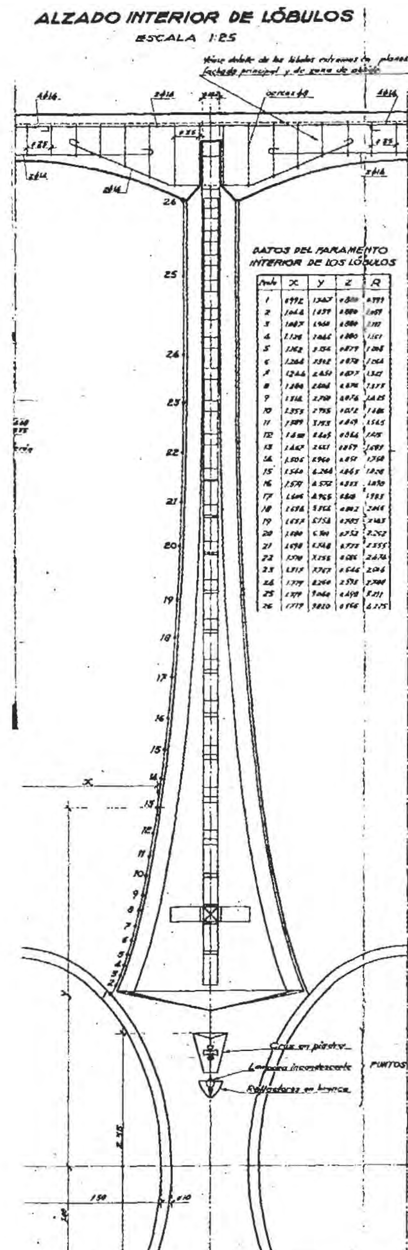

Figura 13
Longitudinal section of the nave. In the table on the right of the image are showed the coordinates of point on the lobule's border and the radius of the arch of the lobule's transversal section in this point

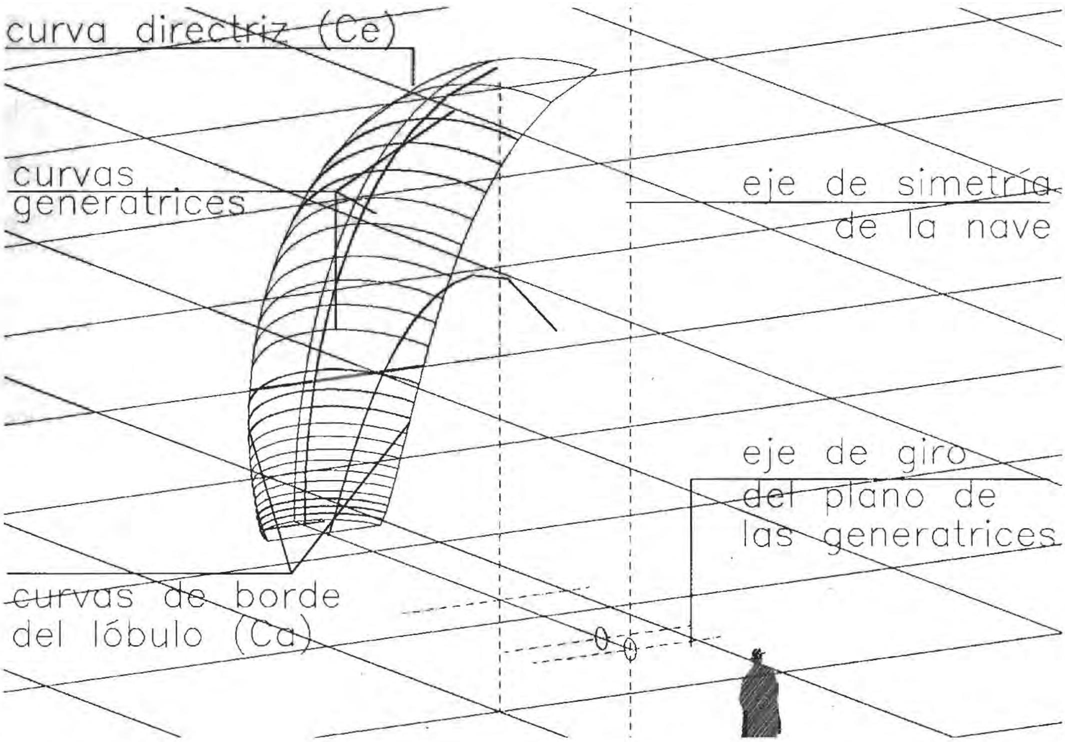

Figure 14
Schema that explain the lines that define the shape of the structure. The laying out con be done whit a simple scaffold, and over them put simple arch braces with the shape of the corresponding circular arch. This arch braces allow to place the "rasillas" of the first layer.

The structural analysis

The structure is a symmetrical arc. For the analysis the expressions used are that ones who appeared in Torroja (1951,9).

Taking these considerations, the maximal stress in the start is -7,7 kg/cm^2 (compression) and +6,2 kg/cm^2 (tensile) (figure 15)

Conclusions

The main characteristic of the Pyrenees' churches cupola is the construction system.

The traditional reinforced trimel vault as support to erect a reinforced concrete shell avoiding the formwork.

The concrete and masonry working stress are weak, about a 10% of the admissible resistance of the material.

Discussion

In the beginning of 20th century, the constructions using reinforced concrete increase a lot. The success of the new material was so big that today is besides the steel structures the main system of construction. However since mid 19th century several test to improve the quality and performances of brick masonry structures using different iron reinforcements have been done. For builders and designers in the first yeas of 20th century the use of steel reinforced masonry works were commonly used. Torroja belongs to the age group of designers that know a number of techniques to construct in addition to rein-

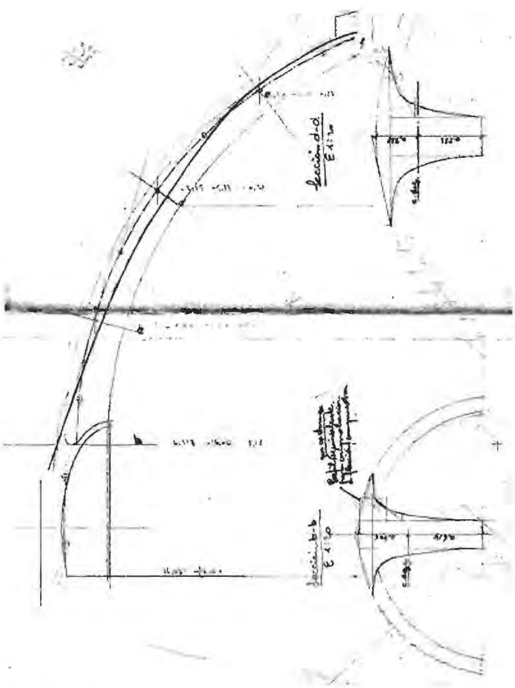

Figure 15.
Transversal section of the nave. The pressures curve obtained from the elastic analysis is indicated.

forced concrete; techniques that some times can be a advantageous competitor for concrete.

In Torroja's work a permanent innovation aim as well as a new proposals for construction appears. The projects with timbrel reinforced vaults were the result of this research.

The purpose is to offer alternatives to construct concrete reinforced shells when problems with cost of auxiliary means in developed countries make them difficult to be used.

In our view, the construction in clay masonry has two different considerations. These considerations are shown respectively in the works of Eladio Dieste and Eduardo Torroja.

The difference is the used that is given to the masonry work.

For Dieste's way, formwork to place the reinforcement and the bricks are needed. (This comment is only in relation with roofing structures, where variable transversal section isostatics beams are used, the comment is not applicable for the construction of towers or walls where the use of formworks are not needed)

In contrast, for Torroja the formwork is not needed because he use the masonry work as formwork.

There are other difference and has a mechanical nature.

Since in Dieste' way of working the masonry works at high stress, in Torroja's one the stress only is up the 15% of the load bearing of the structure

Conclusions

The reinforced trimelt vaults construction were the point for lots of studies in the last years, and the use of reinforced vaults have been recuperated in some cases. The improvements of this kind of structures obtained mixing the vaults with steel mashes and concrete layers is a technique appeared in the earliest stage of the concrete use and has not been studied yet. Apart from the churches in the Pyrenees, reinforced trimel vaults offers possibilities that are not been explored.

The author have proposed in a refurbishment project some of this kind of structures. It is expected they will be constructed in the following months.

Notes

1. In the well-know image of Rondelet (1802) in which show the Sainte Geneviève's church projected by J. G. Soufflot, the disposition of the lintel reinforcement bars are similar to the reinforced bars of current reinforcing bars of concrete beam. This show that in the XVIII century steel bars were used to improve masonry construction.
2. See the patent number 12301 in the "Oficina Española de Patentes y Marcas," 9th july 1891: "objects of plastic material with reinforced frames of wires inside." Following the author, the innovation and the advantage is based in the continuity of the iron wire. The idea is suitable to be used among other in depot, vaults or pipes. In all the cases, the metallic mesh is used as an formwork for a plastic material as cement mortar.
3. In Huerta 1999 it is possible to find quite a lot bibliography about reinforced timbrel vault.
4. The Santi Petri's project, is the document number 19 in the Eduardo Torroja Archive. The remaining documents are those ones where the foundation system is described, The drawings of the bridge, the foundation cais-

sons, and the lateral abutment. Several pictures of the construction process are conserved as well.

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